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H.E.S.S. observations of massive stellar clusters

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Abstract. Stellar clusters are potential acceleration sites of very-high-energy (VHE, $E > 100\text{GeV}$) particles since they host supernova remnants (SNRs) and pulsar wind nebulae (PWNe). Additionally, in stellar clusters, particles can also be accelerated e.g. at the boundaries of wind-blown bubbles, in colliding wind zones in massive binary systems or in the framework of collective wind or wind/supernova(SN) ejecta scenarios. Motivated by the detection of VHE γ -ray emission towards Westerlund 2 and assuming similar particle acceleration mechanisms at work, Westerlund 1 is an even more promising target for VHE γ -ray observations given that massive star content and distance are more favorable for detectable VHE γ -ray emission compared to Westerlund 2. Here, H.E.S.S. observations of massive stellar clusters in general with special emphasis on the most massive stellar cluster in the galaxy, Westerlund 1 are summarized.

1. Introduction

In recent years the field of ground-based VHE γ -ray astronomy experienced a scientific breakthrough due to developments in instrumentation, operation and data analysis of the 3rd generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). Telescope systems like H.E.S.S. (Hinton et al. 2004), MAGIC (Lorenz et al. 2004), VERITAS (Weekes et al. 2002) or CANGAROO-III (Kubo et al. 2004) opened a previously inaccessible window for the study of astrophysical objects at very high energies. Especially the increase of the number of detected VHE γ -ray sources by one order of magnitude is a merit of the Galactic Plane Scan (GPS) performed by the H.E.S.S. Collaboration between 2004 and 2008

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(Aharonian et al. 2006a; Hoppe et al. 2007; Chaves et al. 2008). In the GPS, which covers basically the whole inner galaxy between Galactic longitude $l \sim 275^\circ$ and $\sim 60^\circ$, a rich diversity of astrophysical objects which emit VHE γ -rays was discovered. Even if a large part of the source population lacks of a firm detection in other wavelength bands, a significant fraction of identified objects are connected to the late phases of stellar evolution like e.g. supernova remnants (SNRs) or pulsar wind nebulae (PWN). Moreover, one class of objects emitting VHE γ -rays could be associated to regions of massive star formation and to the birthplaces of the massive progenitors of some SNRs and PWNe, massive stellar clusters.

In this work H.E.S.S. observations of massive stellar clusters with special emphasize on the most massive stellar cluster in our galaxy, Westerlund 1 are presented. After an introduction of the acceleration mechanisms which are at work in such systems (Chapter 2.), recent results of multiwavelength observations and the possible connection of the unidentified source HESS J1614–518 to the stellar cluster Pismis 22 are presented in Chapter 3. The detection of Westerlund 2 (HESS J1023–575) in VHE γ -rays is discussed in Chapter 4. Finally, the detection of VHE γ -ray emission from the vicinity of the massive stellar cluster Westerlund 1 is discussed in Chapter 5.

2. Particle acceleration mechanisms in massive stellar clusters

It is widely believed that massive stars form in groups from the collapse of gas condensations in clumps, inside giant molecular clouds (e.g. Heyer et al. (1998); Williams, Blitz & McKee (2000); Dame et al. (2001); Jackson et al. (2006)). The accretion of cloud material onto the massive stars is stopped, when their winds, outflows and UV radiation leads to the dissipation or disruption of the natal molecular cloud. Depending on the total mass of the system, these groups of stars end as loosely bound *associations* or as dense gravitationally bound *stellar clusters*.

2.1. Massive binary systems

Since a large fraction of massive stars occur in binary (or even triple, quadruple, etc.) systems (e.g. (Zinnecker 2003; Gies 2008) and references therein), the collision of their strong supersonic winds with terminal velocities $v_\infty > 1000 - 5000 \text{ km s}^{-1}$ (Cassinelli 1979), produces strong shocks. Through first-order Fermi acceleration electrons and protons can be accelerated to high energies (Eichler & Usov 1993). Mücke & Pohl (2002), Benaglia & Romero (2003) and Reimer et al. (2006) showed, that detectable γ -radiation up to GeV energies can be generated through inverse Compton scattering of relativistic electrons in the dense photospheric stellar radiation field in the wind-wind collision zone. The detection of non-thermal X-ray emission in massive binary systems like e.g. WR140 (Dougherty 2005) has proven that indeed electrons are accelerated in the wind collision region to relativistic energies. However, just in one hadronic emission scenario (proposed by Bednarek (2005)), a detectable signal by current and future IACTs is predicted. Here, the inelastic scattering of relativistic nucleons on particles in the dense stellar wind produces a significant amount of neutral pions which then decay into VHE γ -rays. Though, at these high ener-

gies, γ -rays suffer from $\gamma\gamma$ absorption which will diminish the observable flux from a close binary system.

2.2. Collective stellar winds

Given the fact, that massive stars mostly occur in associations and stellar clusters, the interaction of their strong supersonic winds leads to the creation of a large collective bubble, also called superbubble (SB), which is filled with a hot and tenuous plasma (e.g. (Weaver et al. 1977)). Turbulent particle acceleration can then take place, where the interaction of wind material forms regions of strong turbulence and MHD waves (e.g. (Bykov 2001; Parizot et al. 2004; Higdon & Lingenfelter 2005; Dwarkadas 2008)).

2.3. SN explosions in stellar clusters

Since massive stars ($M \geq 8M_{\odot}$) end their lives as SN explosions after a few Myrs, an additional contribution of kinetic energy is available to accelerate particles to very high energies. The SNR shell will grow quicker due to the lower density in a SB and in a medium with higher sound speed, due to the higher temperature. This may result in efficient particle acceleration at MHD turbulences and at the boundary of the SB (Parizot et al. 2004; Tang & Wang 2005; Ferrand et al. 2009).

2.4. Implications

In a simplified picture, the aforementioned acceleration mechanisms infer basic properties of stellar clusters, which in principle could indicate the fraction of total kinetic energy in non-thermal particles and therefore a possible emission in VHE γ -rays. One obvious property is the total mass of the cluster, since this directly determines the number of massive stars and therefore the total available mechanical energy in stellar winds (and later in the expanding shells of SN explosions). The age of the stellar cluster (and its mass) further implies whether or not the most massive members already evolved into SNe and finally, the fraction of massive stars located in binary systems defines the contribution from colliding wind binaries (CWBs).

In the next Chapters H.E.S.S. detections of VHE γ -ray sources which could be associated to stellar clusters of different mass, age and distance will be presented.

3. HESS J1614–518

HESS J1614–518 is one of the brightest ($\sim 25\%$ Crab flux, $E > 200$ GeV) unidentified VHE γ -ray sources discovered during the Galactic plane scan (Aharonian et al. 2006a). The region was observed for a total of ~ 13 hours resulting in the detection of an extended, elliptical shaped emission with a half-width of $\sim 0.4^{\circ}$ along the semimajor axis (Fig. 1, left). The overall morphology of the source is well described by a double peak Gaussian profile ($\chi^2 = 0.7$). The differential energy spectrum is compatible with a power law ($dN/dE = \Phi_0 \cdot (E/1 \text{ TeV})^{-\Gamma}$) with a photon index of $\Gamma = 2.26 \pm 0.05_{\text{stat}} \pm 0.06_{\text{syst}}$ and a normalization at 1 TeV of $\Phi_0 = (7.83 \pm 0.40_{\text{stat}} \pm 0.80_{\text{syst}}) \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$.

An analysis of the MSX IR data shows several HII regions and molecular cloud complexes flanking the observed VHE γ -ray emission (Amaral et al. 1991; Matsunaga et al. 2001; Russeil et al. 2005; Li et al. 2006). A search for potential counterparts reveals several interesting candidates (see Fig. 1, right). On the basis of spin-down power of the pulsars in the field-of-view of HESS J1614–518 none of these is powerful enough to account for the total observed VHE γ -ray emission. Nevertheless, a minor contribution is not excluded. Of the Wolf-Rayet ¹ (WR) star WR74, the Ant Nebula and the open stellar cluster Pismis 22, the latter, located at a distance of $d \sim 1$ kpc, is the most promising candidate to explain the observed H.E.S.S. emission (Rowell et al. 2008). Under the assumption that 10 stars of B-type (with 20% efficiency) are associated to Pismis 22 (see Rowell et al. (2008)), their stellar wind luminosities would be sufficient to power the observed VHE γ -ray emission. Additionally, with an estimated age of 40 Myr (Piatti et al. 2000), the system is old enough, that the most massive member stars could have already evolved into SNe, giving an extra contribution to the energy available for particle acceleration. Furthermore, XMM-Newton (Rowell et al. 2008) and Suzaku (Matsumoto et al. 2008) observations revealed an extended non-thermal X-ray emission towards the northern part of the source. Remarkably, the Suzaku ‘Src B’ also shows an extended non-thermal nature and is centred on Pismis 22, similar to other open clusters connected to VHE γ -ray emission, like Cyg-OB2 (Aharonian et al. 2005) or Westerlund 2 (Aharonian et al. 2007).

4. Westerlund 2/HESS J1023–575

The prominent giant H II region RCW49 and its ionizing cluster Westerlund 2 are located towards the outer edge of the Carina arm in our Milky Way at a distance of 8 kpc, following Rauw et al. (2007). Recently Chandra discovered ~ 500 point sources in the vicinity of RCW49 (Tsujimoto et al. 2004), with ~ 100 of them spatially coincident with the central open stellar cluster Westerlund 2 (Townsend et al. 2004). Mid-infrared measurements with Spitzer revealed still ongoing massive star formation in RCW49 (Whitney et al. 2004). The regions surrounding Westerlund 2 appear evacuated by stellar winds and radiation, in contrast to the dust distribution in fine filaments, knots, pillars, bubbles, and bow shocks throughout the rest of the H II complex (Churchwell et al. 2004; Conti & Crowther 2004). Radio continuum observations by ATCA at 1.38 and 2.38 GHz indicate two wind-blown shells in the core of RCW49 (Whiteoak & Uchida 1997), one surrounding the central stellar cluster, the other a Wolf-Rayet star WR20b. Westerlund 2, is centrally located within RCW49. It contains an extraordinary ensemble of hot and massive stars, presumably at least a dozen OB stars, and two remarkable Wolf-Rayet stars. The binary character of WR20a was only recently established. Both Rauw et al. (2004) and Bonanos et al. (2004) presented solutions for a circular orbit with a period of ~ 3.7 days. The derived inclination angle of $(74.5 \pm 2.0)^\circ$ implies masses of 83.0 ± 5.0 and $82.0 \pm 5.0 M_\odot$ for the primary and secondary component, respectively (Rauw et al. 2004). This

¹These stars are in late phases of the evolution, exhibiting strong winds and large mass-loss rates.

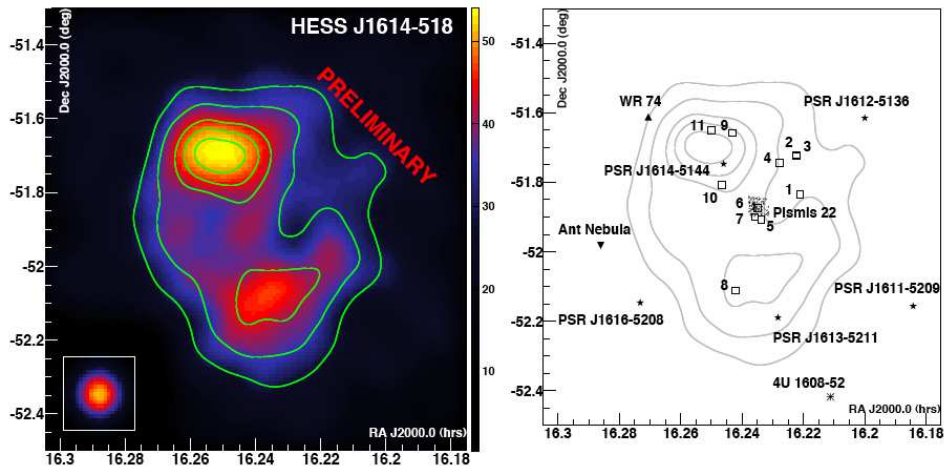


Figure 1. Left: Exposure corrected skymap of the VHE γ -ray excess, smoothed with a Gaussian ($\sigma = 4.2'$). The green contours represent significance levels of 3, 5, 7, 8, and 9σ , after integrating events within an oversampling radius of $\theta = 0.1^\circ$. The bottom left inset shows how a point-like source would have been seen by H.E.S.S. for this analysis after Gaussian smoothing. Right: Finder chart for various objects discussed in the text. Black unfilled squares depict X-ray sources. Member and surrounding field stars are also shown for the open cluster Pismis 22 (from Piatti et al. (2000), labeled as Pismis 22). Figure taken from Rowell et al. (2008).

puts the Wolf-Rayet binary WR20a as the most massive of all measured binary systems in our Galaxy.

H.E.S.S. observed the region around Westerlund 2 in 2006 where a point source analysis on the nominal position of WR 20a resulted in a clear signal with a significance of 6.8σ . Further investigations revealed an extended excess with a peak significance exceeding 9σ (Fig. 2 left, (Aharonian et al. 2007)). The source is clearly extended beyond the nominal extension of the point spread function (PSF), a fit of a Gaussian folded with the PSF of the H.E.S.S. instrument gives an extension of $0.18^\circ \pm 0.02^\circ$ (Aharonian et al. 2007; Reimer et al. 2007). The differential energy spectrum for VHE γ -rays inside the 85% containment radius of 0.39° can be described by a power law ($dN/dE = \Phi_0 \cdot (E/1 \text{ TeV})^{-\Gamma}$) with a photon index of $\Gamma = 2.53 \pm 0.16_{\text{stat}} \pm 0.1_{\text{syst}}$ and a normalization at 1 TeV of $\Phi_0 = (4.50 \pm 0.56_{\text{stat}} \pm 0.90_{\text{syst}}) \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. The integral flux above 380 GeV is $(1.3 \pm 0.3) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$.

The detection of VHE γ -ray emission from the vicinity of Westerlund 2 can be explained by different acceleration mechanisms. One possibility is the conversion of kinetic energy available in the colliding-wind region of the binary system WR20a into the acceleration of particles to very high energies. Given the fact, that no significant flux variability could be detected in the data set and since the observed excess is extended with respect to the H.E.S.S. PSF, an association between WR20a and the VHE γ -ray emission is not striking. Alternatively, the emission could arise from the collective stellar wind effects in the Westerlund 2 cluster. As discussed before, particles are accelerated by multiple shocks and

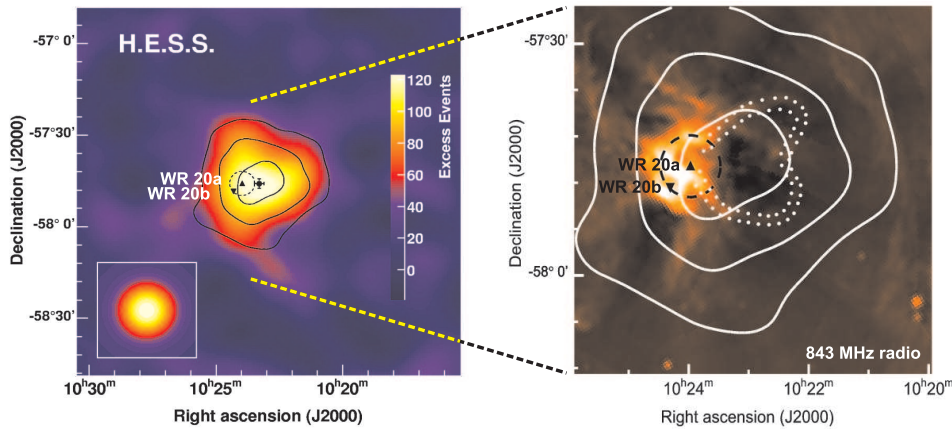


Figure 2. Left: H.E.S.S. γ -ray count map (oversampling radius of 0.12°) of the Westerlund 2 region. The inlay in the lower left corner shows how a point-like source would have been seen by H.E.S.S. WR 20a and WR 20b are marked as filled triangles, and the stellar cluster Westerlund 2 is represented by a dashed circle. Right: Significance contours of the γ -ray source HESS J1023–575 (5, 7 and 9σ), overlaid on a MOST radio image. The wind-blown bubble around WR 20a, and the blister to the west of it can be seen as depressions in the radio continuum. The blister is indicated by white dots as in Whiteoak & Uchida (1997), and appears to be compatible in direction and location with HESS J1023–575. (Figure taken from Reimer et al. (2007)).

interact with the dense photon field of the stellar winds. However, the VHE γ -ray spectrum is expected to be similar that of SNRs at energies below 1 TeV. Particle acceleration by MHD motions (shocks, turbulence, etc.) of magnetized plasma produced by supersonic flows, which then penetrate into a dense medium may also be important under these conditions (Bykov 2001). The massive stellar winds of Westerlund 2 could ensure sufficient particle injection into the turbulent plasma, feeding of magnetic turbulence with energy by wind-wind interactions of the massive star association, and the allocation of enough target material for the VHE γ -ray production.

5. Westerlund 1

Motivated by the detection of VHE γ -ray emission towards Westerlund 2 and assuming similar particle acceleration mechanisms at work, Westerlund 1 (Wd 1) is an even more promising target for VHE γ -ray observations given that massive star content and distance are more favorable for detectable VHE γ -ray emission compared to Westerlund 2.

Westerlund 1 is the only known super star cluster in our galaxy. With a total mass of $\sim 6 \times 10^4 M_\odot$, it is currently the record holder in terms of its rich content of stars in the Wolf-Rayet phase. At least 24 WR stars are known of which $>70\%$ are expected to be in binary systems (Groh et al. 2006). Additionally the existence of more than 80 blue super-giants, 3 red super-giants, one luminous blue variable and 6 (out of 12 in the whole galaxy) yellow hyper-

giants is reported in several papers (summarized in Munro et al. (2006b)). The dissipated power in the form of kinetic energy in the wind of the WR stars alone is $L_W \approx 10^{39}$ ergs s⁻¹. Given an age of ~ 5 Myrs (Crowther et al. 2006), the most massive stars in Wd 1 evolved into SNe. Assuming furthermore a SN rate of 10^{-4} yr⁻¹, the available kinetic energy for particle acceleration would be quadrupled (Munro et al. 2006b).

X-ray observations with the Chandra satellite have revealed a magnetar candidate (AXP CXOU J1647-4552, $P = 10.6$ s) with a massive progenitor which is associated with Wd 1 (Munro et al. 2006a). A detailed analysis also revealed extended emission (of the order of arc minutes) which deviates from the typical thermal emission that can be seen from many other stellar associations. With increasing distance to the cluster core, the hard non-thermal emission dominates and line-emission disappears. The total luminosity observed in X-rays amounts to $L_x = 3 \times 10^{34}$ ergs s⁻¹ (Munro et al. 2006b), representing just 10^{-5} of the total mechanical luminosity in this system. The same authors discuss various possibilities to explain the ‘missing energy’ in this powerful system, amongst others, the dissipation beyond the Chandra field-of-view by a large scale outflow and radiation at other wavelengths. Recent measurements suggest a distance of the cluster of 4-5 kpc. Whereas the estimates by Brandner et al. (2005) and Crowther et al. (2006) depend on the star content of the cluster and therefore suffer from extinction, Kothes & Dougherty (2007) investigated the neutral environment of Wd 1 to find emission and absorption features in the HI data which could be connected to the stellar cluster. Interestingly they find two small expanding bubbles with dynamical ages of ~ 0.6 Myrs and a large interstellar bubble with a size of 50 pc and a dynamical age of 2.5 Myrs at a distance of 3.9 ± 0.7 kpc.

H.E.S.S. observed the Westerlund 1 region from 2004 - 2007 during the GPS and in pointed observations for 14 hrs under good weather conditions (according to the Standard quality selection (Aharonian et al. 2006b)) with the full array at zenith angles below 55°. Another 22 hrs of good quality data was obtained in observations conducted between May - August 2008, resulting in a total data set of 34 hrs live-time². Preliminary and previously unpublished H.E.S.S. results of these observations reveal a spatially extended emission region of VHE γ -rays with a total significance of $> 15\sigma$, within an integration radius of 1° around the Wd 1 position (85% containment) (Fig. 3, left).

The extension of the VHE γ -ray emission exceeds 2° in diameter, making it one of the largest structures observed in VHE γ -rays so far. A total of > 2300 γ -rays are detected within the 34 hours of livetime. The threshold of the analysis is at 680 GeV.

Among the ‘established’ classes of counterparts for VHE sources like SNRs and PWNe only PSR J1648-4611 is coincident with the observed γ -ray emission. Given its \dot{E}/d^2 of 6.2×10^{33} ergs s⁻¹ kpc⁻² it can contribute to the VHE γ -ray emission. Recently, the LAT instrument on board of the Fermi satellite detected unpulsed emission from a region coincident with the pulsar position (Abdo et al. 2009). The Low Mass X-ray Binary (LMXB) GX 340+0 and other point-like counterparts are unlikely, given the rather extended nature of the

²observation time, corrected for the dead-time of the system

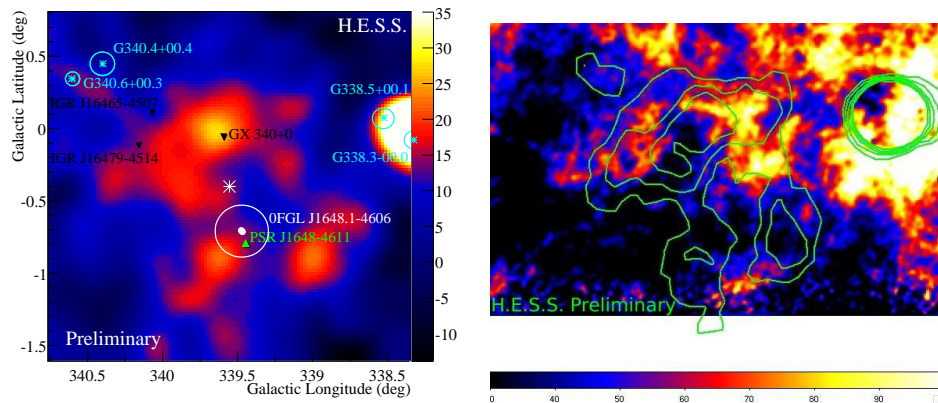


Figure 3. Left: Preliminary gaussian smoothed H.E.S.S. γ -ray count map ($\sigma = 0.13^\circ$) of the region around Wd 1 (indicated as white star), filled green and black triangles mark INTEGRAL sources and the pulsar PSR J1648–4611, respectively. Cyan circles represent SNR candidates from Greens catalogue (Green 2004). The white circle indicates the Fermi bright source OFGL 1648.1–4606 (Abdo et al. 2009). The bright region on the right is the known H.E.S.S. source HESS J1640–465. Right: HI channel map of the Southern Galactic Plane Survey (SGPS) at a velocity of -55 km s^{-1} (McClure-Griffiths et al. 2005) corresponding to a distance of $\sim 4 \text{ kpc}$ as obtained by Kothes & Dougherty (2007). Color scale from 20 K to 100 K, overlaid are the preliminary H.E.S.S. significance contours from 4 to 8 σ in steps of 1σ after integrating events within 0.22° radius (as done for the analysis of slightly extended sources compared to the H.E.S.S. PSF in the GPS).

VHE γ -ray emission. A radial profile of the excess counts per square degree in rings of 0.1° width starting from the Westerlund 1 position is shown in Fig. 4. The VHE γ -ray emission from within the optical boundary of the stellar cluster (the innermost ring) is consistent with the overall picture of a rather flat emission out to a distance of $\sim 0.9^\circ$ from the Wd 1 position (a fit of a constant yields a moderate χ^2/ndf of 14.6/8). Fig. 3, right shows preliminary H.E.S.S. significance contours from 4 to 8 σ in steps of 1σ after integrating events within 0.22° on top of the HI channel map at a velocity of -55 km s^{-1} , corresponding to the distance to Wd 1 as derived by Kothes & Dougherty (2007). The comparison may suggest a correlation between the VHE γ -ray emission and the HI data in some parts. Further spectral and morphological studies of the H.E.S.S. emission and observational data in radio and X-rays could help to shed some light on the origin of the TeV γ -ray emission and its possible connection to the super star cluster Westerlund 1.

6. Discussion

Massive stellar clusters provide sufficient kinetic energy in stellar winds, colliding wind binary systems and from collective wind and/or wind/SNe ejecta effects to accelerate particles to relativistic energies. After the detection of VHE γ -rays from the direction of the open stellar cluster Cyg-OB2 by the HEGRA

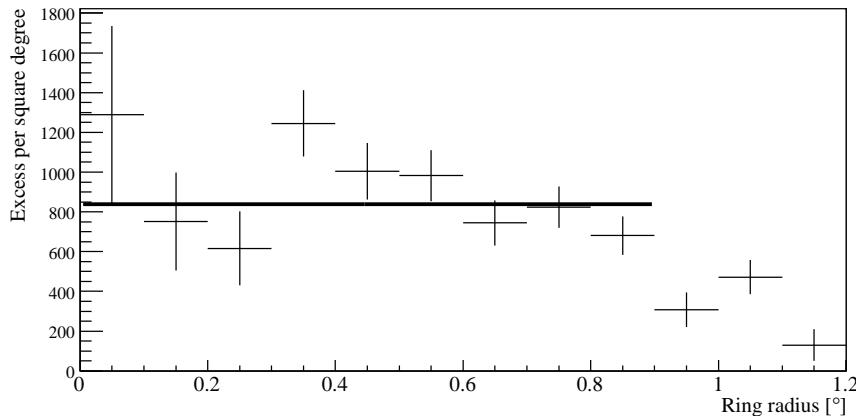


Figure 4. Preliminary radial profile of the uncorrelated γ -ray excess sky map starting at the Westerlund 1 position (white star in Fig. 3, left).

Collaboration (Aharonian et al. 2005), H.E.S.S. discovered a source, coincident with the stellar cluster Westerlund 2. Furthermore, one of the brightest unidentified H.E.S.S. sources, HESS J1614–518, seems also be connected to a stellar cluster, Pismis 22. Westerlund 1 as the most massive stellar cluster known in our galaxy is a perfect target for VHE observations given its massive star content, age and binary fraction. The detection of extended emission from the vicinity of Westerlund 1 has been reported in this work. All these results suggest that multi-TeV particle acceleration may be linked to several massive stellar clusters.

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